REPORT DOCUMENTATION PAGE

Form Approved

AFRL-SR-BL-TR-98-

0444

1. AGENCY USE ONLY (Leave Blank) 16

2. REPORT DATE
June 1994

3. REPORT T
Final

4. TITLE AND SUBTITLE
A New Low Cost Unfurlable Beam for Small Spacecraft Applications

5. FUNDING NUMBERS

6. AUTHORS
Jeffery D. Goss and Martin M. Mikulas, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Colorado, Boulder

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NI
110 Duncan Avenue, Room B-115
Bolling Air Force Base, DC 20332-8080

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
See attached.

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

19980518 024

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

DTIC QUALITY INSPECTED 5

A New Low Cost Unfurlable Beam for Small Spacecraft Applications

by

Jeffery D. Goss‡ and Martin M. Mikulas, Jr.‡‡

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June 16, 1994

Abstract: *In this paper a new concept for a light weight, low cost, small packaging volume, unfurlable beam is presented. Two hardware models are constructed and deployment tests conducted. The first test involves the measuring of accelerations as the structure is horizontally deployed along a Teflon sheet. The second test involves strobed photography of a vertical deployment. From these tests the assumption of a constant deployment force is verified. The deployment force is then analytically solved for using the time for deployment from the horizontal deployment test.*

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A New Low Cost Unfurlable Beam for Small Spacecraft Application

by Jeffery D. Goss and Martin M. Mikulas, Jr.

Introduction

Due to the string of recent spacecraft failures, a renewed emphasis has been placed on small inexpensive spacecraft. On these spacecraft, beams are needed for deployment of solar arrays, antennas, and instruments requiring distance from the main body of the craft. In the past thirty years considerable research has been done to design deployable beam structures for various space missions. These beams range from small unfurlable beams to large mechanical hinged beams. The beams include strain energy deployed STEMs and BI-STEMs, the motor deployed Minimast, and hybrids such as the continuous longeron masts which use motor controls to regulate a strain energy deployment.

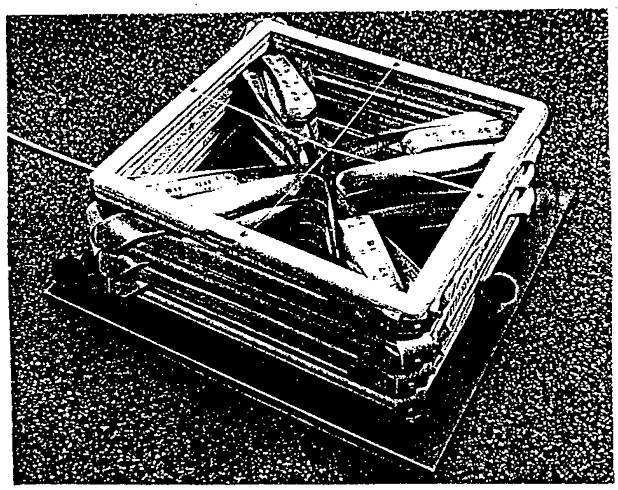
STEMs, Storable Tubular Extendible Members, consist of a flat strip of metal, which is heat treated such that the unstressed state is an overlapping tube[5]. STEMs are packaged by flattening one end of the tape and rolling it onto a drum of large enough diameter to avoid introducing permanent strain. On release of the free end, the tape rolls off the drum and extends into a tube-shaped mast utilizing only its own strain energy. BI-STEMs operate under the same principle but consist of two drums of tape which when released form concentric tubes. The result is a light, simple, and reliable deployable beam which has been used on spacecraft for the last thirty years. However, STEMs and BI-STEMs have low bending and torsional stiffnesses and posses a relatively high coefficient of thermal expansion (CTE). These last characteristics recently led to control disturbances in the Hubble telescope and have limited the telescope's effectiveness.

On the other end of the spectrum lies the Minimast as described in reference 1. The Minimast is a three longeron truss of graphite epoxy tubes with hinges at the end of each longeron and midway along each batten and diagonal. The mast is deployed by screwjacks which pull up each of the three corners. Once the bay's hinges are locked, the next bay is deployed. Packaging requires a set of manipulator arms to push the diagonals' center hinges inward while batten hinges are collapsed by the stress of packaging. The Minimast exhibits a very high stiffness and low CTE, but because of the titanium hinges and screwjack deployment mechanisms, the mast is also heavy. The weight of the truss and its complex deployment and packaging mechanism are undesirable in today's aerospace community when the emphasis is on "miniature" spacecraft.

The continuous longeron mast has initially straight longerons which are twisted and coiled such that the mast compresses into a canister. The diagonals are made of cable and collapse under compression. On opening the canister, the coils untwist and spring upward using the stored strain energy. A motor and cable are used to control the speed of the release as well as for repackaging of the beam. A mast of this type was used in the Solar Array Flight Experiment (SAFE) conducted by the Langley Research Center on STS-41D[8]. These masts have very detailed and complex joints and consequently are highly specialized and expensive in application.

In this paper a new deployable beam, which was conceived specifically to address the requirements of small, low cost spacecraft, is introduced. This new beam is a four longeron truss which makes use of "carpenter's tape" unfurlable members to eliminate mechanical joints and maximize simplicity and yet possess a high deployed bending and torsional stiffness. A prototype of this beam was built and demonstrated using off-of-the-shelf steel "carpenter's tape". This relatively simple to make beam has demonstrated very high deployed stiffness and compact stowage characteristics. The beam characteristics

can be tailored to a wide variety of requirements including size, stiffness and precision. This paper includes a concept description, a method of evaluation, a detailed model description, the results of some deployment tests, and a simple deployment analysis.



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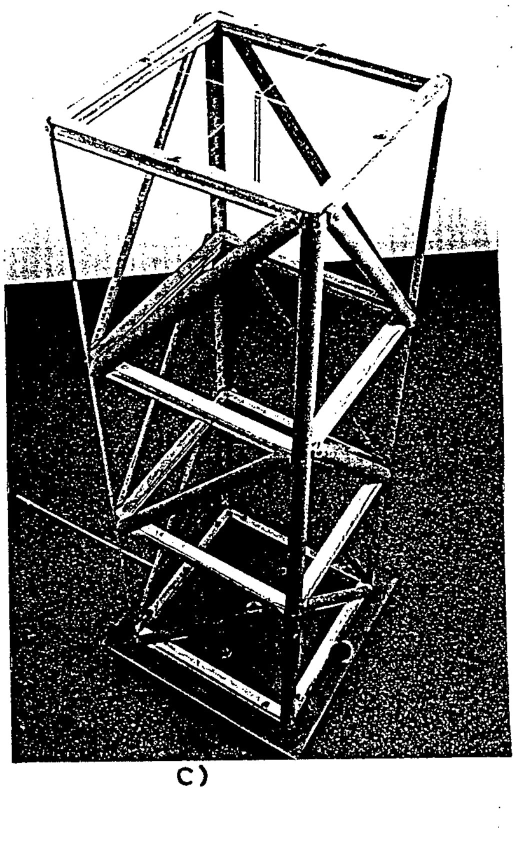

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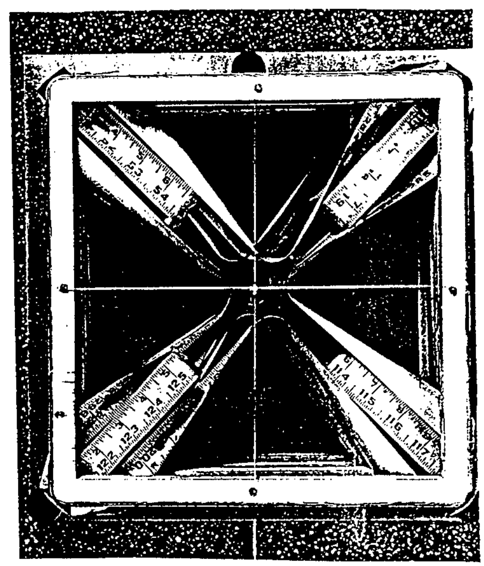

a)

Figure (1) Photographs of Three Bay Tape Truss
a) overhead view, packaged b) isometric view, packaged
c) isometric view, deployed

Concept Description

The Unfurlable Strain Energy Tape Truss (USETT) is a cubic bay truss beam which utilizes strain energy for sequential deployment of its bays. The beam is designed with small satellite users in mind. Some possible uses for such a beam are the deployment of antennas, solar arrays, masses for gravity gradient stabilization, and instruments which need separation from an electromagnetically noisy spacecraft. Design drivers for the beam include simplicity in deployment mechanisms, small packaging volume, low cost, and low weight.

The longerons and diagonals of the truss beam are made of a curved tape similar to a roll-up "carpenter's tape". In fact, for the prototype models, "carpenter's tape" is being used. For high performance applications these steel tapes could be replaced by curved composite graphite tapes. The tapes serve both as structural members and the deployment mechanism for the beam.

As seen in Figure (1), the diagonals of any one face of the beam are parallel to each other. The parallel configuration was used to counteract construction problems. When attempting to attach two diagonals to the same point, the tapes were perpendicular to each other and the longitudinal curvatures prevented the tapes from fitting firmly together. Four solutions were considered. The tapes could have been deformed and bolted to the batten plane on top of each other, or one diagonal could have been offset inward from the other. Either of these options results in a loss of stiffness. The third option involved increasing the batten plane thickness to allow each diagonal to be fixed to half of a batten plane. This option was discarded because it resulted in an increased packaging volume and weight. The final option involved parallel lacing of the diagonals. While some torsional stiffness loss is incurred when compared to an ideal truss lacing, the parallel lacing of the diagonals seemed the best solution to dealing with finite sized, curved members.

The beam is packaged by bending the longerons and diagonals radially inward and clamping the top batten plane to the base of the structure (See Figure (1)). The bends in the tapes play the role of hinges. Due to the thin nature of the tapes, the beam's packaged height is only slightly greater than the combined thickness of the batten planes. Deployment is achieved by releasing the clamp and allowing the strain energy stored in the bent tapes to push against the adjacent batten planes.

This strain energy manifests itself as a moment present at each transition zone between flattened and curved sections of the tape. A transition zone exists on either side of a bend. The moments on opposite sides of the central bend act in opposite directions. These moments may be translated into two forces, one of which deploys the first half of the structure and the other of which serves as an anti-deployment force on the next batten plane. The initial assumption modeled the force applied by the unfurling tapes as a constant. Data from the experiments correlate with this assumption.

At the instant of release, all batten planes except the top plane are in equilibrium from tapes pushing in opposite directions. Because the top plane has tapes on only one side, the top plane accelerates outward away from the packaged truss. As the batten plane moves away, the force exerted by the tapes of the first bay remains constant. This constant force results in a net zero force on the second and subsequent batten planes and causes these planes to remain packaged. After the first bay's tapes snap straight, strain energy is no longer present and no force is applied from the longerons and diagonals of the first bay. The second batten plane is then no longer in equilibrium and the deployment process continues. The resultant deployment is sequential.

Concept Evaluation

In order to validate the concept of the Unfulable Strain Energy Tape Truss, experiments were performed which demonstrateed the deployment characteristics of the truss and gave insight into the forces present during deployment.

To this end, a three bay model and a one bay model were constructed. At this preliminary stage, wooden batten planes and "carpenter's tape" longerons and diagonals sufficed. The model was then deployed and accelerations measured by means of struccells. The struccells were mounted in triaxial blocks on each batten plane of the structure and measured accelerations in the three principle axis of the Cartesian coordinate frame.

An acceleration versus time matrix was recorded for each struc cell using a data harvester and signal processing unit. The results were then written to a computer file and the plotted. Rapid decceleration was present on the graph where the tape snaps through to lock into its final position. By observing this decceleration, the time of deployment was measured.

A strobed photograph deployment experiment was performed on a one bay USETT. A single photo was exposed to multiple flashes of a strobe. From the photographs, a position vs time plot was created. A polynomial for position as a function of time was found and the force as a function of time was derived from this polynomial.

To validate the order of the forcing function, a Simulink™ model was created. Plots of position vs. time were made and the time of deployment was compared to the accelerometer data. Once the order of the forcing function was found, the force of deployment was analytically solved given the structural mass, the time of deployment, and the initial conditions.

Model Description

Two test models currently exist: a one bay and a three bay beam. Each bay is a cube 11.5in. on a side from midpoint to midpoint. Because of material beyond the batten mid plane, the overall one bay length is 12.25 inches and the three bay length is (34.5+2*3/8 =) 35.25 inches.

Two primary materials were used. Batten planes were constructed of pine wood, while longerons and diagonals were constructed of "carpenter's tape". The "carpenter's tape" is the standard Stanley measuring tape made of a steel tape coated with plastic. The tape has a one inch chord from side to side. The vital statistics are discussed in the following paragraphs.

Batten Planes

The Batten planes were made of 11.5 in. x 11.5 in. x 3/4 in. pine plates with a square of 10 in. x 10 in. x 3/4 in. material removed from the center. The result is a square "ring" of wood 11.5 in. on a side with a cross section of 3/4 in. x 3/4 in. Exterior edges were routed smooth.

Each board is a composite of 5 layers of pine alternated in grain direction. The material properties are as follows:

young's modulus[1] (E)	= 1.6 e6 psi
weight density[1] (ρ)	= 0.01736 lbs/in^3
calculated weight	=weight density * volume = ρ * (11.5^2 - 10^2)*3/4 = 0.4199 lbs
measured weight	= 0.3799 lbs
percentage difference	= .4199-.3799/.4199 *100 = 9.5%

Because of the variable density and water content of each wooden piece, the measured weights were used.

Longerons and Diagonals

Longerons and diagonals were made of Stanley "carpenter's tape". The tape is a composite of a steel tape sandwiched between two plastic layers. The steel tape is made of a circular central segment with a straight segment on either edge. This formation's cross section approximates a parabola. Physical data is as follows:

weight/ unit length	= 1.32 e-3 lbs/in	
Longeron length	= 11.5 in	(center of batten plane to center of batten plane)
Longeron weight	= 0.015 lb	
Diagonal length	= 15 in.	(center of batten plane to center of batten plane)
Diagonal weight	= 0.0198 lb	
Total thickness (t_{tot})	= 0.008 in.	
metal thickness (t)	= 0.004 in.	
plastic thickness	= 0.002 in. each side	

L = 0.906 in
Δ= 0.197 in

R = L^2 / (8*Δ) = 0.5211 in
parabolic approximation

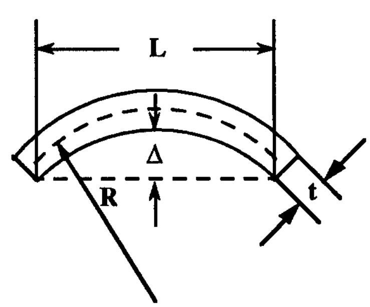

Figure (2.) Tape cross section.

Assembled product

Longerons, diagonals, and batten planes were assembled into a "z truss" formation. Opposite diagonals on the same bay were perpendicular while all diagonals on the same face of the truss beam were parallel. This formation was necessary to prevent overlap of diagonals at the attachment points.

Longerons were attached with curves into the rounded corners of the batten planes by a single screw midway along the batten plane. Theoretically, there were four longerons per bay. In actuality one contiguous longeron was run from bottom batten plane to top batten plane with screws attaching the longeron to each batten plane.

Diagonals were attached such that they did not overlap a longeron. This offset resulted in diagonals that were 15 inches long rather than the 16.5 inches which occur in an ideal square of 11.5 inches on a side. To accommodate the curve of the diagonal, wooden shims were placed between the side of the batten plane and the diagonal. The diagonals were fixed to the batten plane through the shims with two screws .

The final structure was mounted on a 12 in. x 12 in. x 3/4 in. aluminum plate by means of 8 screws placed one inch from each corner. The plate rested on three adjustable feet and was bolted to the floor or a vertical backstop as was required.

The catch, which held the truss in a packaged state, consisted of a nylon rod of packaged beam height + 3/4 in. in length. The rod was attached to the top batten plane by means of two nylon wires running from midpoint to midpoint of opposite sides. The nylon wires were in turn held in place by four screws. A pincher mechanism was mounted on the underside of the aluminum baseplate and was used to clamp onto a groove near the base of the nylon rod. When connected, the pincher and rod held the beam in its packaged position.

Packaging was achieved by bending all tape members of the bottom bay radially inward and then holding the batten planes of the collapsed bays together while each subsequent bay was packaged. After the last bay was packaged, the rod was inserted into and held in place by the pincher. When the pincher was released, the beam deployed by means of strain energy stored in the longerons and diagonals.

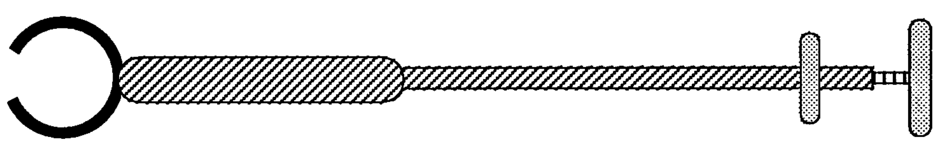

Figure (4.) Pincher Mechanism

Total weight calculations

Part count

(n = number of bays)		1bay	3bay
battons planes	= n + 1	2	4
longerons	= 4n	4	12
diagonals	= 4n	4	12
screws	= 12(n+1) + 4	28	52
wires	= 2	2	2
rods	= 1	1	1

Part weight

Longeron weight	= 0.015 lb
Diagonal weight	= 0.0198 lb
Batton plane weight	= 0.3799 lbs
Screw weight	= 1.76e-3 lb
Wire and Rod weight	= 6.4e-3 lb

Total weight

1bay

$$\begin{aligned} W &= 2\times bat.\ wt. + 4\times Long.\ wt. + 4\times Diag.\ wt. + 28\times screw\ wt. + wire\ and\ rod\ wt. \\ &= 0.95 \text{ lb} \end{aligned}$$

3bay

$$\begin{aligned} W &= 4\times bat.\ wt. + 12\times Long.\ wt. + 12\times Diag.\ wt. + 52\times screw\ wt. + wire\ and\ rod\ wt. \\ &= 2.03 \text{ lb} \end{aligned}$$

Deployment Experiments

Two deployment experiments were performed in order to obtain an understanding of the forces present during deployment. In the first experiment, AC accelerometers, struccells, were used to record the accelerations of the first and second bays of the three bay truss as it deployed horizontally. The second experiment consisted of strobed photography of a one bay truss deploying vertically against gravity.

In the horizontal deployment experiment, the three bay truss and baseplate were mounted on a vertical backstop (see Figure (4)). Triaxe blocks holding struccells were glued on the exterior vertical surfaces of the first and second batten plane. Two bays of the truss were deployed horizontally along an oiled Teflon sheet of 1/8th inch thickness. The third bay was strapped to the baseplate to prevent deployment. This bay was not used because of concerns over damage previously done to its longerons and diagonals. Accelerations were recorded at a sample frequency of 5000 Hz using a Kinetic Systems model 1502 data acquisition device, a data harvester from Piezotronics, and Lambdas, which is an in-house data collection and analysis program develop by Mr. Steve Bullocks and Mr. Scott Doebling of the Structural Design and Control Laboratory at the University of Colorado, Boulder.

Initially, steel nuts were used as feet to interface between the truss and the Teflon. This interface created too much friction for a smooth deployment. Ice blocks were attached to the end of the steel feet to reduce the deployment friction. Although the friction was greatly reduced, it could not be completely removed and the top edge of each batten plane continued to tip forward during deployment. A prow was constructed of "carpenter's tape" and added to the first batten plane to prevent the top edge of the structure from tipping forward. With this configuration (see Figure (4)), smooth, even, horizontal deployment was achieved.

Three samples of the accelerometer data may be seen in Figure (5),Figure (6), and Figure (7). Figure (5) shows the full time range of data taken. Thse graphs represent accelerations in the deployment direction. The initial flat line segment represents time after sampling has begun but before release of the structure. At approximately 0.7 seconds, the structure was released. This may be seen as a sudden jump upward to just over 1 g. As the first bay deploys, the structure is seen to vibrate around this 1 g level. As the tapes snap through into their locked positions, the first bay decelerates rapidly. This deceleration and the accompanying large magnitude, high frequency vibration is readily visible on the graph at 0.25 seconds. The second bay's snap through corresponds with the start of the second large magnitude vibration near 0.38 seconds.

Figure (6) represents an enlargement of the first bays deployment between 0 and 0.3 seconds. Using this graph and by manually entering the deployment data matrix, the start and stop times of the first bay's deployment were found. The start time was taken as the first acceleration reading beyond the nominal background noise. This event occurred at 0.70 seconds. The stop time was taken at the first consecutive data points with negative accelerations (0.25 seconds). Therefore an elapsed deployment time of 0.18 seconds was found. Additional trials confirm this data.

Under the constant force assumption, deployment would be sequential. The second batten plane would be held in equilibrium by the equal forces on either side until the first bay was fully deployed. At that time, the second batten plane would no longer be in equilibrium and would begin deployment. This phenomenon was visually confirmed and is visible in Figure (7). Figure (7) shows the acceleration data measured from the second bay as the first bay deploys. The release point is again readily visible as the structure begins vibrating. However, unlike Figure (6), this bay vibrated around zero g's. The second bay remained in its packaged position. This requires the forces from the tapes of the first bay to have equaled or exceeded the forces from the tapes of the second

bay. A second experiment was performed to determine the tape forces as a function of time.

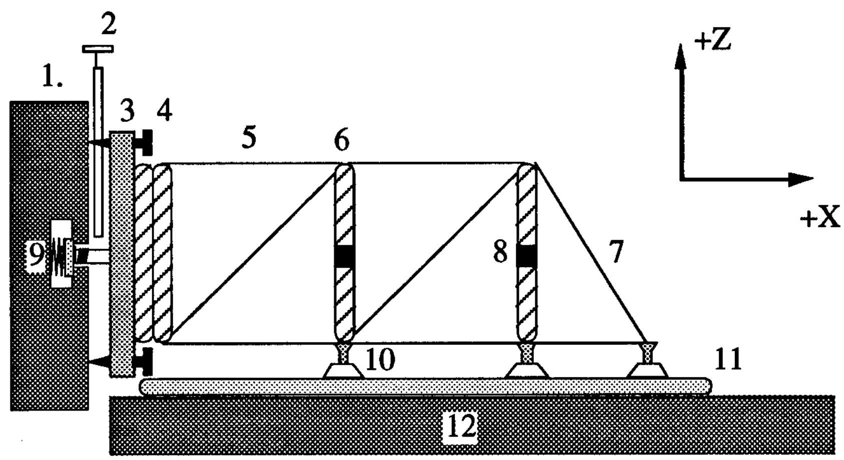

Figure (4)
Horizontal Deployment Test Setup

1. Steel Backstop - Attached to Floor
2. Release Mechanism - Attached to Baseplate
3. Aluminum Baseplate - Attached to Backstop by 9
4. Adjustable Feet - Used to Level Structure
5. Longerons and Diagonals - Constructed of "Carpenter's Tape"
6. Wooden Batten Planes - Leftmost Plane Bolted to Baseplate
   -Second Plane Held Down to Prevent Deployment
   -Third and Fourth Planes Denoted as Second and First Bays Respectively
7. "Carpenter's Tape" Prow - Added to Prevent Tipping
8. Triaxe Blocks - Hold Struccells (wires not shown)
9. Bolt and Unistrut Attachment - Holds Baseplate to Backstop
10. Support Feet / Ice Blocks - Low Friction Interface between Structure and Sliding Surface
11. 1/8" Teflon Sheet - Low Friction Sliding Surface; Oiled
12. Table - Provides Level Support to Prevent Bending During Deployment

The second experiment involved strobed photography of a one bay USETT as it deployed vertically against gravity. The one bay USETT and its baseplate were secured to a table. A yard stick was attached to the black background for scale. The camera was secured to a tripod approximately two yards from the truss with the strobe approximately two and a half yards from the truss. The strobe frequency was set using an oscilloscope. Ten flashes with 0.03 seconds separation and one camera shutter opening of length 0.5

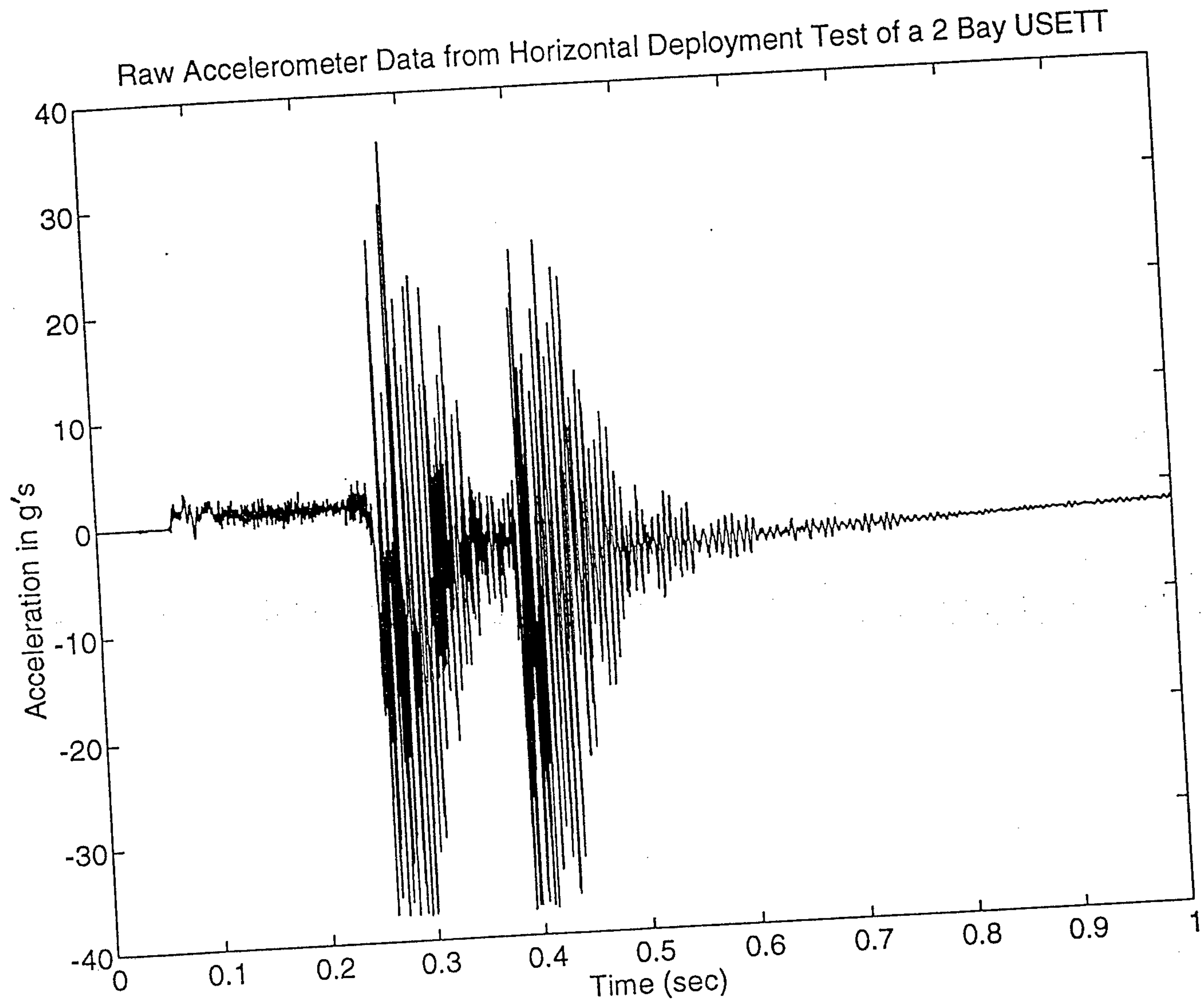

Figure (5)
Raw Accelerometer Data from
Horizontal Deployment Test

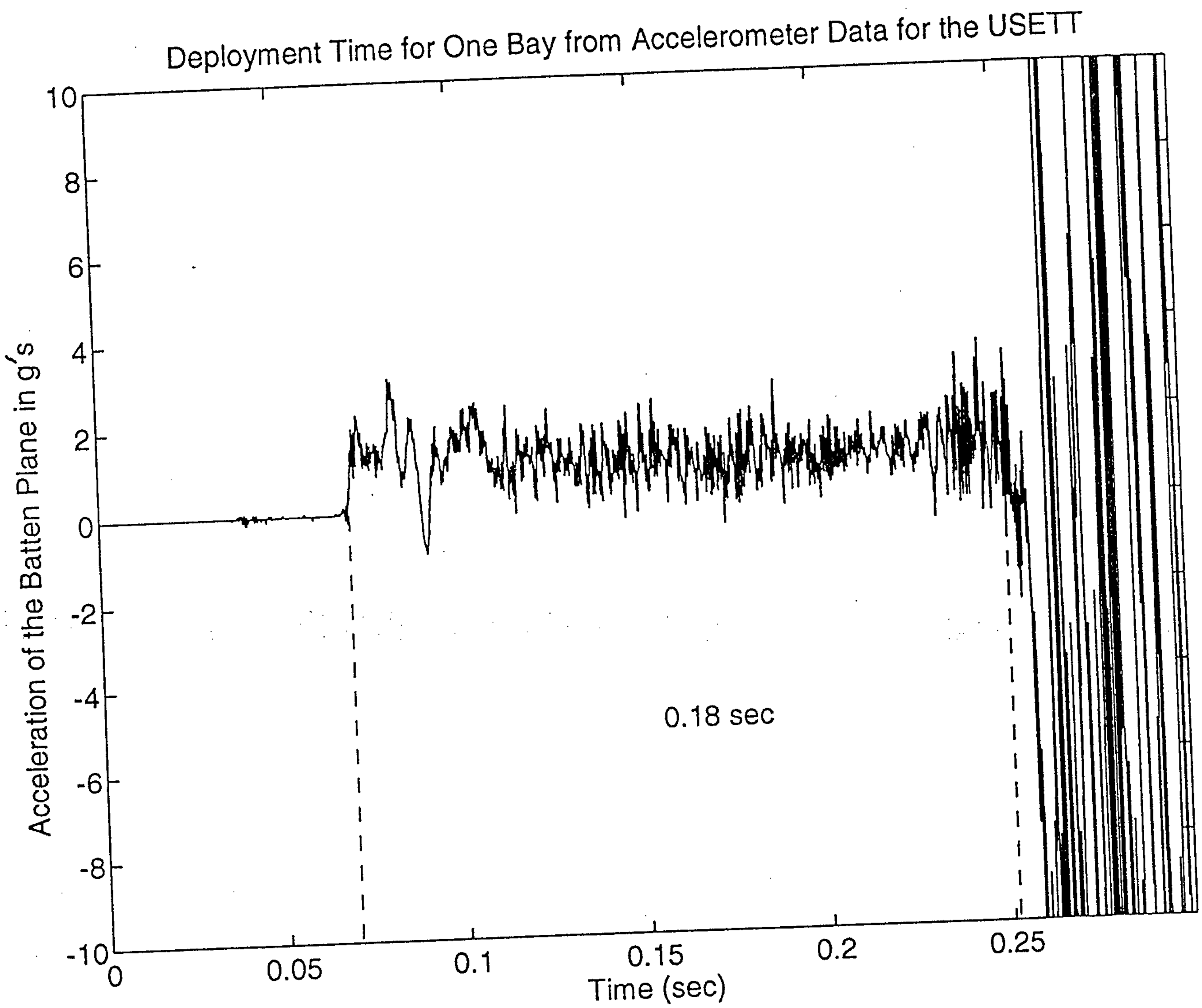

Figure (6)
Enlargement of Horizontal Deployment Data
Time of One Bay Deployment

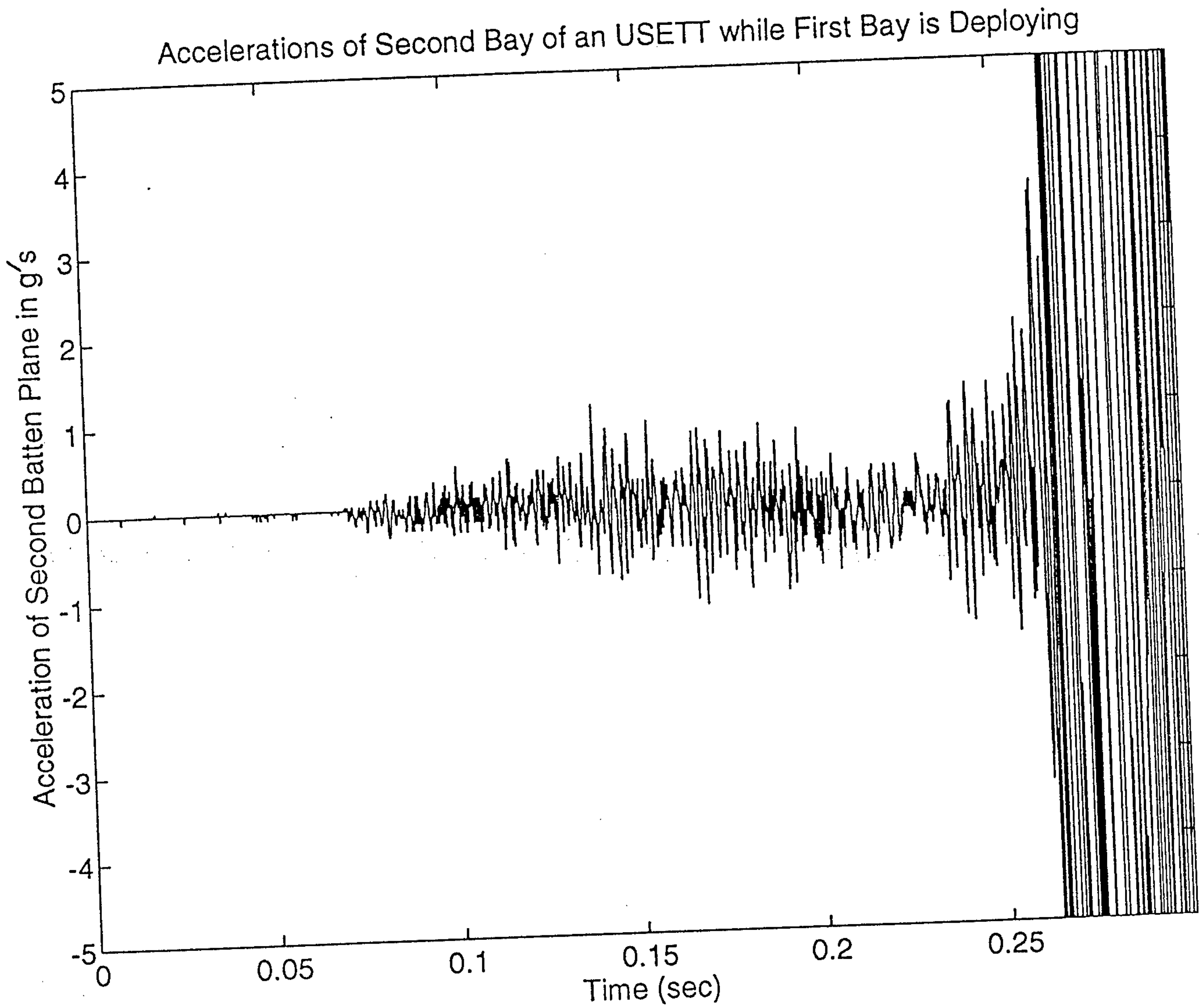

Figure (7)
Accelerometer Data from Horizontal Deployment Test
as Recorded from Second Bay Sensors

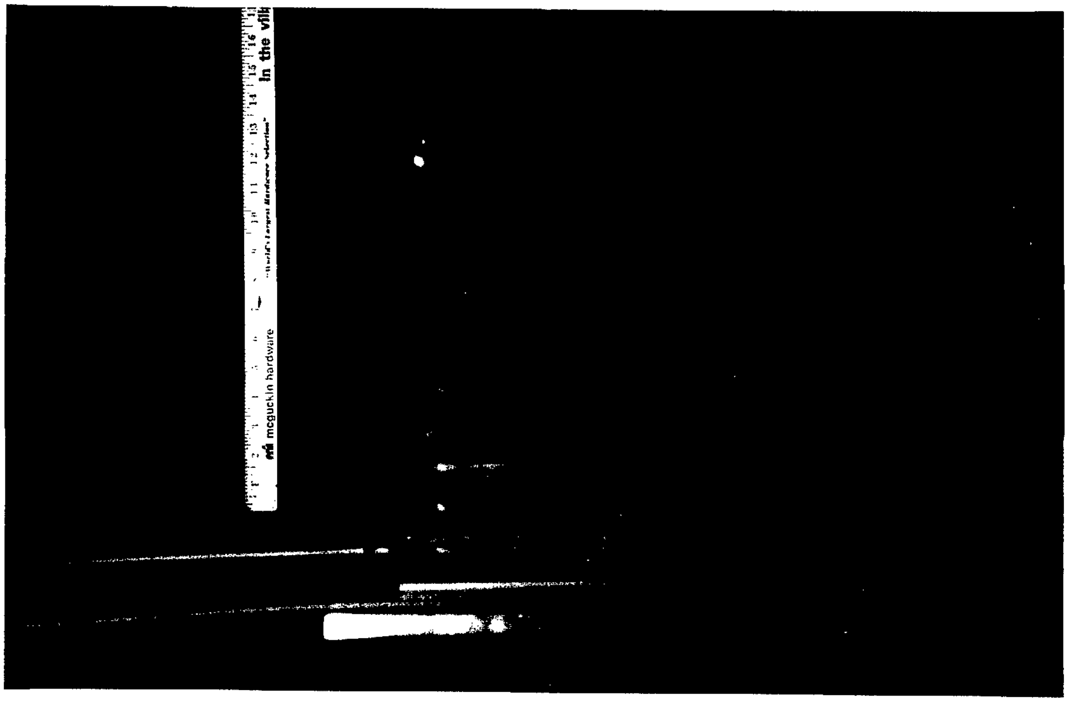

Photo 1

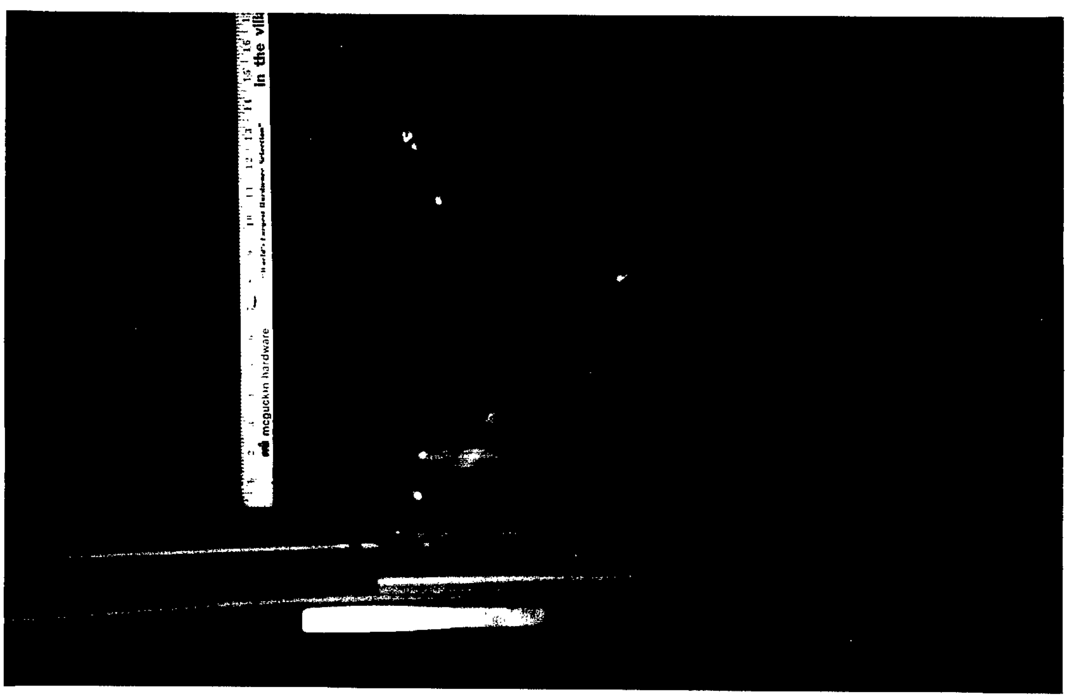

Photo 2

Figure (8)
Strobed Photography of One Bay USETT Deployment

seconds occurred during each deployment trial. The strobe/camera and the USETT release were operated manually by the experimenter. The resulting photos, Figure (8), show multiple positions of the upper batten plane during deployment. These exposures may be used to calculate position as a function of time from which the forcing function may be found.

The positions of the upper batten plane were measured from 8x10 photos using a ruler graded to a sixteenth of an inch. Distances were measured from the midpoint between the two longeron screws on the bottom batten plane to the midpoint between the two longeron screws on the upper batten plane. The scale was determined by measuring the distance represented by one inch on the yardstick in the photograph. It was discovered that the yardstick in the photograph had been distorted disproportionately to the truss in the development process. When measured by the yardstick in a duplicate photograph, the 12 inch truss appeared to be 15 inches tall. Therefore the final scale was determined to be 3/8 * 15/12 inch = 1 inch or 0.46875 inch = 1 inch. The distances measured from the photographs were divided by 0.46875 to obtain the distance deployed.

Since the strobe and structural release were manually triggered, the time to the first exposure could not be accurately determined. Therefore the first exposure was used as time = 0 with a subsequent Δt of 0.03 seconds per exposure. In each of the photographs the last exposure occurred before complete deployment and could therefore be used as an accurate data point.

The following table contains the measurements and their transformation to real data.

Photo 1 Base Batten to ... (in inches)	Time (sec)	Measured Data	Real Data
1st Exposure	0	1.000	2.1333
2nd Exposure	0.03	1.46875	3.1333
3rd Exposure	0.06	2.125	4.5333
4th Exposure	0.09	3.000	6.4000
5th Exposure	0.12	4.0625	8.6667
6th Exposure	0.15	5.40625	11.5333
Photo 2 Base Batten to ...			
1st Exposure	0	1.0625	.2667
2nd Exposure	0.03	1.59375	3.400
3rd Exposure	0.06	2.3125	4.9333
4th Exposure	0.09	3.45625	6.7333
5th Exposure	0.12	4.25	9.0667
6th Exposure	0.15	5.5625	11.8667

Figure (9) Strobe Experiment; Upper Batten Position vs. Time

The real data vectors and the time vector were input to Matlab and various polynomial fits were tried. A second order polynomial adequately modeled the displacement as a function of time. A third order polynomial did not increase the accuracy significantly. The polynomials found were ,

$$P_{photo1} = 253.96x^2 + 25.25x + 2.15$$

$$P_{photo2} = 228.85x^2 + 29.29x + 2.29$$

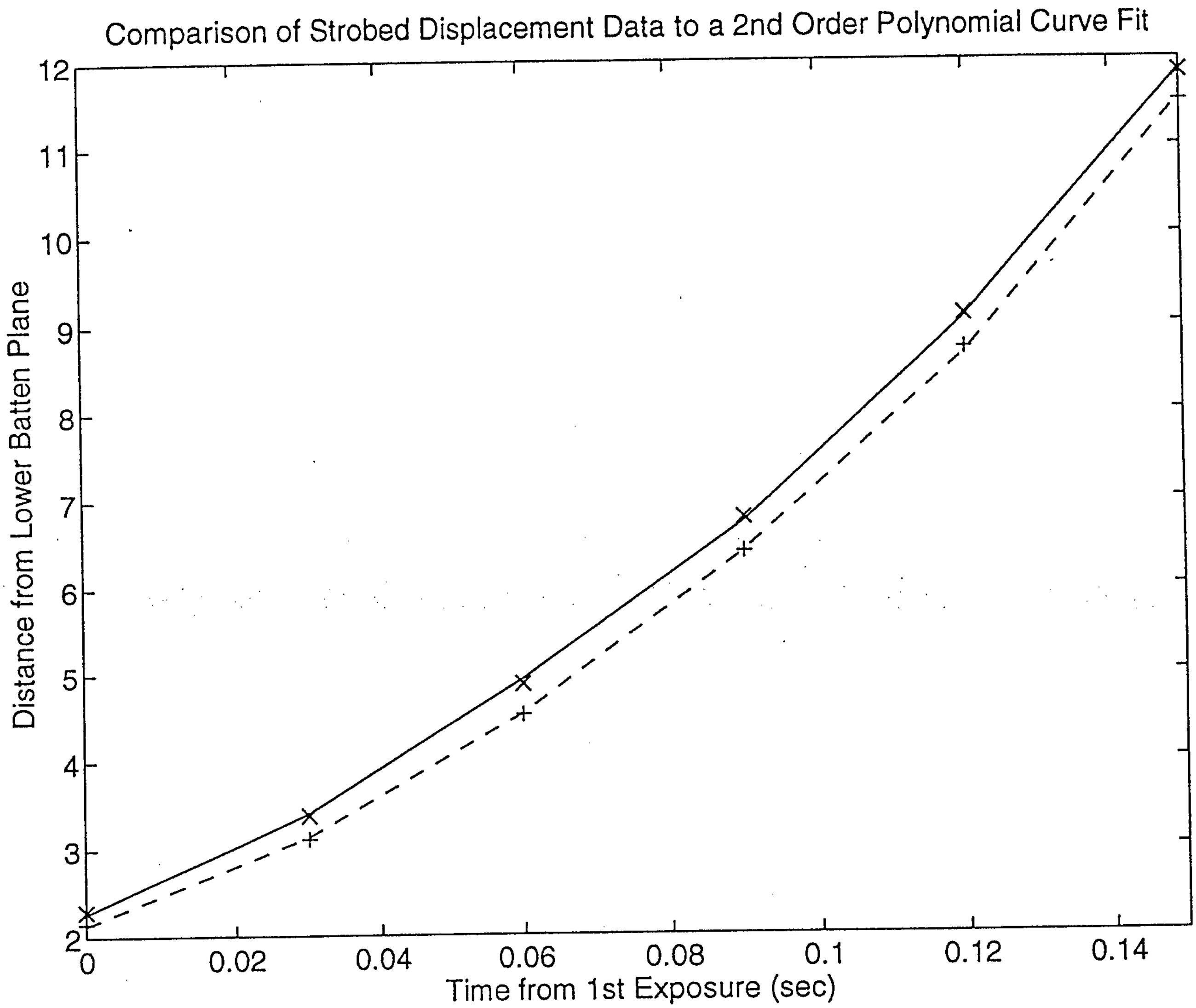

Figure (10)
Strobed Photography Displacement Data
Overlaid with Points from Polynomial Simulations

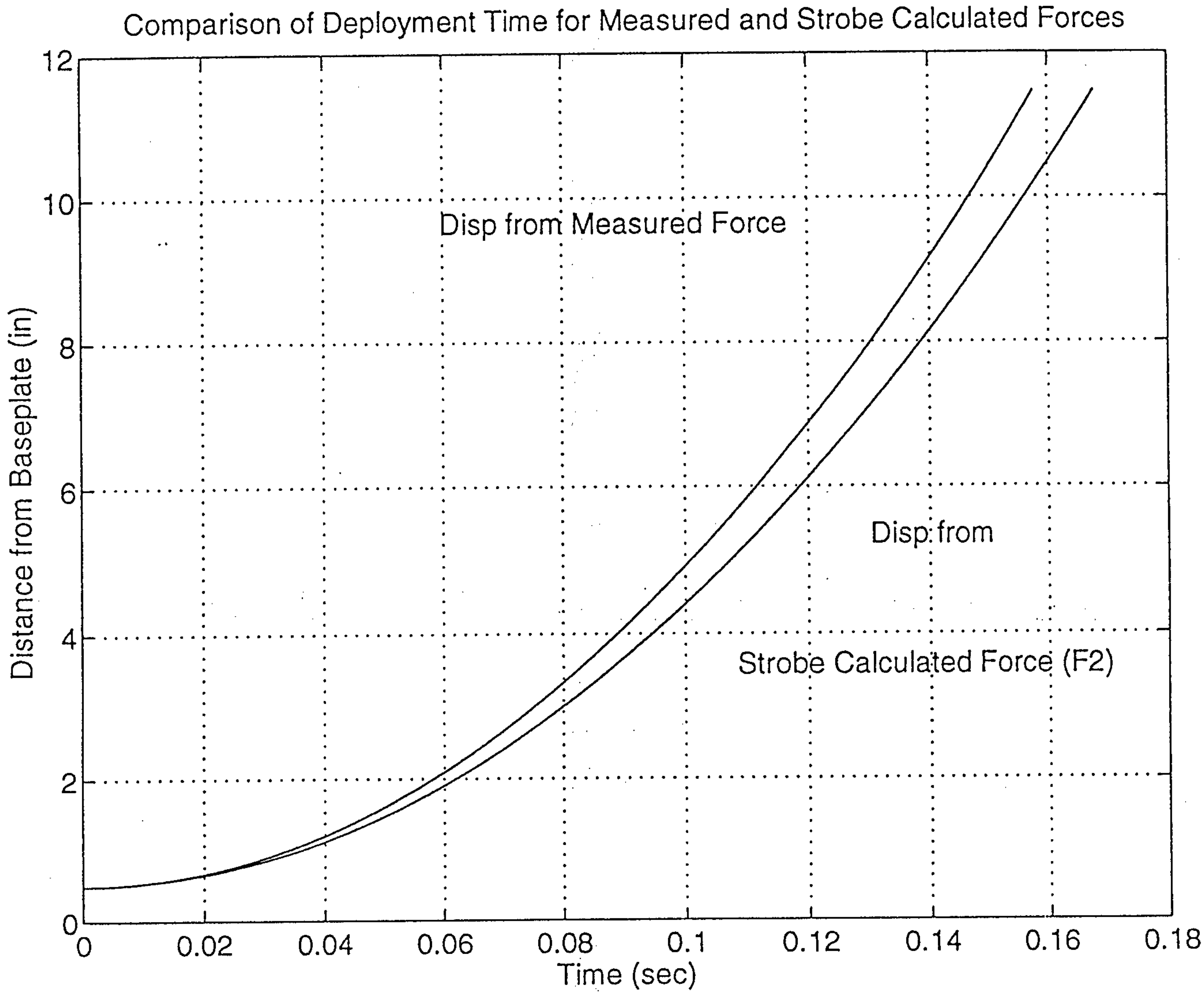

Figure (11)
Deployment Time for Tensile Scale Measured Force, F_{scale}
and Strobe Calculated Force, F_{photo2}

where x is in inches. The plot of the real data from the strobe photography and its simulation using these polynomials may be seen in Figure (10).

The force was found by taking the two derivatives of the displacement function and multiplying by the mass lifted, f = ma. However this force is the net force deploying the one bay vertically against gravity. The total force, F, also lifted half of the weight of the structure. F was then found from

$$f = F - m/2 \times g \quad \Rightarrow \quad F = f + m/2 \times g$$

$$F_{photo1} = 1.10$$

$$F_{photo2} = 1.04$$

These are the forces which must be used when comparing deployment times between a simulation and the horizontal deployment test.

A rough estimate of F was found by using a tensile scale to find the force required to keep the truss packaged. The force of deployment as measured by the tensile scale, F_{scale}, was found to be 1.175 lb. The tensile scale was found to be inaccurate at low values but the measurement served to verify the magnitude of the forces derived from the photography. A numerical integration simulation of the deployment was run using a second-order runga-kutta method and the forces from the photos and the tensile scale. The results for F_{photo2} and F_{scale} are shown in Figure (11).

Both forces give a simulated deployment time within 0.02 seconds of the accelerometer measured deployment time. The time of deployment using F_{photo2} was 0.17 seconds, which is within 5.6% of the accelerometer measured deployment time of 0.18 seconds. Given the inaccuracy of the strobe measurements, this agreement verified the constant force assumption.

Analytical Model

Using the constant deployment force model, the applied force, F, was computed analytically. Starting from the equations of motion, the calculations were as follows:

$$F = m\ddot{x} \quad \Rightarrow \quad x = \frac{1}{2}\frac{F}{m}t^2 + C_1 t + C_2$$

$$\Rightarrow \quad x = \frac{1}{2}\frac{F}{m}t^2 + V_0 t + x_0$$

where $x_0 = V_0 = 0$. Then applying the boundary condition $x_{t=0.18} = 11.5in = 0.9583ft$ and using m equal to the half of the structural mass,

$$F = \frac{2mx}{t^2} = \frac{2 \times (0.95lb / 32.2ft / \sec^2) / 2 \times 0.9583ft}{(0.18\sec)^2}$$

$$\Rightarrow F = 0.875 \ lb.$$

For one bay deployment, this force gives a final analytical model of

$$x = \frac{1}{2} \times \frac{0.875}{m} t^2$$

$$= \frac{0.4375}{m} t^2$$

Conclusions

In this paper the concept of the Unfurlable Strain Energy Tape Truss (USETT) has been validated. A three bay and a one bay model of the truss have been constructed and successfully deployed both horizontally and vertically.

An initial assumption was made that the forces of deployment were constant and would result in sequential deployment. These forces were caused by the strain energy stored in the bent longerons and diagonals. Two experiments were performed in order to test this assumption.

The first experiment involved deploying two bays of the three bay truss horizontally along a Teflon sheet. The accelerations experienced by the batten planes were recorded. From the time of release to the instant of tape snap through, the accelerations of the first bay were seen to vibrate around a constant value just over 1 g in magnitude. A deployment time of 0.18 seconds/bay was found. While the first bay was deploying, the accelerations of the second bay were seen to vibrate around zero g's. From this data, it was concluded that the first bay underwent a constant acceleration while the second bay remained in place, verifying the constant force/sequential deployment assumption.

A second experiment involving strobe photography was performed to verify the accelerometer test and to calculate a value for the force of deployment. The one bay model was deployed vertically and multiple exposures were taken on a single frame of film. The data from these photos was simulated using a second order polynomial for the distance deployed as a function of time. From this function a constant deployment force of 1.03 lb. was calculated. Deployment times between the accelerometer data and the forcing function were within 5.6%.

Using the experimental deployment time, the initial conditions, and the verified constant force assumption, the force of deployment was calculated analytically from the equations of motion. The analytically derived force was found to be 0.875 lb.

Finally, a polynomial expression for distance deployed as a function of time was created from the equations of motion and the analytically derived deployment force.

Through these models and experiments, the USETT has been verified as a valid concept for the sequential deployment of a light weight, low cost, square bay truss beam with a small packaging volume.

References

1.) Adams, Louis R.: Design, Development and Fabrication of a Deployable/Retractable Truss Beam Model for Large Space Structures Application. Nasa Contractor Report 178287, June 1987

2.) MacNaughton, J.D.: "Unfurlable Metal Structures for Spacecraft", Canadian Aeronautics and Space Journal, April 1963, pp. 103-116

3.) Mantell, Charles L.: Engineering Materials Handbook, McGraw-Hill 1958

4.) Rimrott, F.P.J: "Two Secondary Effects in Bending of Slit Thin-Walled Tubes", Journal of Applied Mechanics, March 1966, pp. 75-78

5.) Rimrott, F.P.J: "Storable Tubular Extendible Member .... a unique machine element", Machine Design, December 9, 1965, pp.156-165

6.) Warden, Robert M.: Folding Articulated Square Truss, 21st Aerospace Mechanisms Symposium , Houston,Texas April 29-May1, 1987, NASA Conference Publication 2470

7.) You, Z. and Pellegrino S.: Dynamic Deployment of the CRTS Reflector, SDM Conference, 1994, AIAA Paper No. 94-1504-CP

8) Young, Leighton E. and Pack, Homer C.: Solar Array Flight Experiment/Dynamic Augmentation Experiment, NASA Technical Paper 2690, February 1987

9.) Young, Warren C.: Roark's Formulas for Stress and Strain, McGraw-Hill 1989